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LIFE CYCLE IMPACT ASSESSMENT (LCIA)

Quantifying anthropogenic mobilization, flows (in product systems) and emissions of fixed nitrogen in process-based environmental life cycle assessment: rationale, methods and application to a life cycle inventory

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Abstract
Purpose Anthropogenic perturbation of the nitrogen cycle is attracting increasing attention as both an environmental and societal concern. Here, we provide the rationale and propose methods for independent treatment of anthropogenic mobilization, flows (in product systems) and emissions of fixed nitrogen in process-based environmental life cycle assessment.
Methods We propose a simple methodology for aggregating N flows in life cycle assessment (LCA), with supporting characterization factors for all nitrogen-containing compounds on the Organization for Economic Cooperation and Development High Production Volume Chemical List for which specific chemical formulae are available, as well as all nitrogen-containing flows in the International Reference Life Cycle Data System. We subsequently apply our method and characterization factors to a life cycle inventory data set representing a subset of the consumption attributable to an average EU-27 consumer and compare the results against previously published estimates for nitrogen emissions at the consumer level that were generated using alternative methods/approaches.
Results and discussion We derive a suite of over 2,000 characterization factors for nitrogen-containing compounds. Overall, the results generated by applying our method and characterization factors to the European Commission Basket-of-Products life cycle inventory data set are consistent with those observed from studies having a similar scope but different methodological approach.
Conclusions This outcome suggests that anthropogenic mobilization, flows (in product systems) and emissions of fixed nitrogen can, indeed, be systematically inventoried and aggregated in process-based LCA for the purpose of better understanding and managing anthropogenic impacts on the global nitrogen cycle using the methods and characterization factors we propose.

Keywords Life cycle assessment (LCA) · Life cycle impact assessment (LCIA) · Life cycle inventory (LCI) · Nitrogen cycle · Reactive nitrogen

1 Introduction

Nitrogen is essential to all life forms. Despite being the most abundant element in the Earth's atmosphere, most nitrogen exists in a stable form (N_2) that is biologically inaccessible until fixed in a reactive form (N_r). This nitrogen "bottleneck" was historically a limiting factor in biological productivity and carbon storage, with the magnitude and distribution of nitrogen fixation pathways strongly influencing ecosystem composition (Vitousek et al. 1997).

Environmental fixed nitrogen levels fluctuated little during the 2,000 years prior to the industrial revolution, when a significant upward climb began (Erisman et al. 2008) as a result of increased food, chemical and energy production. At present, human activities contribute more fixed N to terrestrial ecosystems than do all non-anthropogenic sources combined. Background levels have effectively doubled since 1970 (Vitousek et al. 1997; MEA 2005; Galloway et al. 2004, 2008) and continue to rise rapidly.

Increasing the supply of fixed N in the nitrogen cycle has numerous consequences, including increased radiative forcing,

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stratospheric ozone loss, photochemical smog formation and acid deposition, and productivity increases (in particular, linked to eutrophication) leading to ecosystem simplification (decreased diversity) and biodiversity loss (Socolow 1999; Galloway et al. 2003, 2004, 2008; Sutton et al. 2011a). Moreover, reactive nitrogen is known to cascade through ecosystems, sequentially contributing to these impacts as it cycles from one form to another (Galloway et al. 2003, 2008; Sutton et al. 2011a, b).

Nitrogen fixation is also among the most energy-demanding of human activities, and a leading contributor to the growing energy intensity of agriculture and food systems (Pelletier et al. 2011). In face of energy price increases and volatility, this has non-trivial implications for access to nitrogen—in particular, in economically disadvantaged areas—with knock-on consequences for food security (Pelletier et al. 2011). Increasing nitrogen use efficiency (i.e. the amount of nitrogen necessary per unit of product output) and optimizing allocation of nitrogen resources is hence an important socio-economic as well as environmental objective.

Most human-mediated nitrogen fixation is for crop fertilization—either via ammonia synthesis (used in industrial fertilizer production) (63 %) or biological nitrogen fixation (24 %) (Sutton et al. 2011b). Under status quo technological and consumption norms, the projected near doubling of global food production volumes by 2050 (FAO 2006) relative to 2000 will further exacerbate perturbation of nitrogen cycle dynamics (Pelletier and Tyedmers 2010). The remaining 13 % of global anthropogenic contributions of fixed nitrogen is attributable to high temperature combustion—in particular, the combustion of fossil fuels—and other industrial processes (Sutton et al. 2011b), which will likely similarly continue to increase as a result of energy-dependent economic growth (Pelletier et al. 2011).

However, uses of nitrogen for non-fertilizer purposes are proportionally more important in industrialized countries. For example, while Yara (2009) suggests that 83 % of ammonia produced globally was used for fertilizer production, Jensen et al. (2011) and Leip et al. (2011a) report that, taking exports into account, industrial and other non-fertilizer uses appropriate approximately one third of total ammonia produced in Europe. Moreover, the need for N and the source of N emissions change with both industrialization and urbanization. For example, Gu et al. (2012) found that absolute nitrogen input to the Greater Shanghai area increased by over 1,000 % between 1952 and 2004, with the majority of emissions shifting from agricultural to industrial and urban sources. Also, in addition to contemporary nitrogen fixation, extraction and use of fossil fuels mobilizes significant quantities of pre-historically fixed nitrogen into the global nitrogen cycle.

Due to growing recognition of the magnitude of human dependence on and perturbation of the nitrogen cycle, and attendant potential social, human health and environmental consequences (Socolow 1999; Vitousek et al. 2009; Galloway et al. 2003, 2004, 2008; Sutton et al. 2011a), research to quantify the magnitude and distribution of reactive nitrogen mobilization, flows in economic systems and losses is increasingly visible. For example, the European Nitrogen Assessment was established “to review current scientific understanding of nitrogen sources, impacts and interactions across Europe, taking account of current policies and the economic costs and benefits, as a basis to inform the development of future policies at local to global scales” (Sutton et al. 2011b). Cucek et al. (2012) compared the carbon and nitrogen footprints of fossil fuel versus biomass-derived energy generation, showing that trade-offs exist when substituting between these energy sources. Leach et al. (2012) proposed a methodology for an “N footprint” calculator for quantification of personal N footprints, which is now publically available on-line. A link between dietary choice in Europe and total losses of nitrogen has recently been established by Westhoek et al. (2013), and Leip et al. (2013) calculated the N-footprint for 12 main food categories covering most of EU food production (with the exception of fish and seafood production). Although this wealth of recent research has usually been based on life cycle thinking, consistency and comparability of studies are hampered by the current lack of common methodologies. Arriving at robust and consistent quantification of the magnitude and distribution of fixed N mobilization, flows and losses, and effective management strategies, will be facilitated by the application of common life cycle-based tools and approaches.

A subset of nitrogen species are already accounted for among the flows that are quantified in several impact assessment methods commonly used in life cycle assessment, including methods for calculating global warming, acidification, eutrophication and ozone depletion potential. Each of these methods is relevant at particular spatial scales and may also be influenced by context-specific factors—both biogeochemical and anthropogenic. However, to date, the rationale and supporting methodological guidance for quantification of total fixed nitrogen mobilization, flows (in product systems) and losses in life cycle inventories, along with supporting characterization factors for aggregating N species, is lacking. As a result, N is not typically specifically considered as a stand-alone inventory or impact assessment issue in LCA research.

Given the potentially serious consequences of continued perturbation of the global N cycle as a result of anthropogenic mobilization and losses of fixed N, as well as the likelihood that management of N will be increasingly prominent in policy agendas for both environmental and socio-economic reasons (Sutton et al. 2011a, 2013), we suggest

that a consistent inventorying and quantification method for N in LCA research is desirable.

Specifically, a reactive nitrogen inventory and impact assessment method should enable quantification of the distribution and magnitude of N flows both within the technosphere and across the technosphere/ecosphere boundary (both as resource and emissions). Such an approach should not be misinterpreted as double counting, since the purpose is not to account for the specific impacts of particular N species that are already included in other impact categories but rather to quantify contributions to the general (but pressing) problem of anthropogenic perturbation of the nitrogen cycle via mobilization and losses of fixed N.

Towards this end, we describe here a simple methodology and provide the necessary characterization factors for consistent treatment of N as a stand-alone inventory and impact assessment issue in process-based environmental LCA. The method is primarily intended to support quantification of aggregate losses of fixed N in order to better understand anthropogenic perturbation of the N cycle. However, the inventories developed for such assessments can also subsequently be used to support calculations of N-use efficiency and nitrogen footprints.

We apply our characterization factors to a previously compiled life cycle inventory data set representative of a subset of consumption attributable to the average consumer in the 27 member states of the European Union (EU-27) in key demand categories for the base year 2006 (European Commission 2012a, b). These results are compared to previously published, comparable estimates that were generated using other approaches in order to test the efficacy of our proposed method.

2 Methods

Implementation of a new method for systematic inventorying and aggregation of nitrogen mobilization, flows in product systems and emissions in life cycle assessment requires two steps: classification and characterization.

2.1 Classification of nitrogen compounds

Classification is the process of assigning all flows in the life cycle inventory to the appropriate environmental compartments (i.e. in terms of the impact categories to which they contribute). Explicitly accommodating N mobilization, flows in product systems and losses to the environment in life cycle inventories and impact assessment therefore requires the identification of all resource, product and waste flows that contain N compounds, and the discrimination of those that are retained in the technosphere from those that cross the technosphere–ecosphere boundary as emissions to water, air or soil. This, in effect, constitutes a systematic N mass balance exercise across the life cycle.

2.2 Characterization of nitrogen compounds

Characterization is the process of assigning characterization factors to all flows tabulated in the life cycle inventory so as to facilitate quantification and aggregation of potential impacts in terms of a common reference species. Since the impact of concern is anthropogenic perturbation of the N cycle via mobilization and losses of fixed N, this necessitates assigning N-equivalent factors to nitrogen-containing compounds—a relatively straight-forward process requiring calculation of the ratio of N mass to total molecular mass for each compound of interest in the inventory. Table 1 lists characterization factors for a small subset of common nitrogen-containing compounds.

Inventoried nitrogen-containing compounds must be characterized as resource, product or waste flows in order to facilitate evaluating the distribution of N mobilization, flows and losses. All fixed nitrogen-containing compounds may be considered to contribute to the perturbation of the N cycle when released as waste flows into air, water or soil. Aggregation of emissions of fixed N following assignation of an appropriate N characterization factor for each nitrogen-containing flow will provide the sum of fixed N-equivalent emissions representing the total human addition of fixed N to the N cycle for the product life cycle of concern.

Denitrification is a microbially mediated process of nitrate reduction that, through a series of intermediate gaseous nitrogen oxide products, returns N_r to its most thermodynamically stable form, nitrogen gas (N_2). Emissions of N_2 must therefore be assigned a characterization factor of 0 in impact assessments which quantify contributions to perturbation of the nitrogen cycle.

Tracking flows of N through product supply chains in order to ensure an accurate mass balance throughout the life cycle and to identify hotspots for use and losses of fixed N will require attention to the distribution of N in numerous products within the technosphere as well as those that are disposed of. Millions of nitrogen-containing compounds exist. Of these, tens of thousands are commercially available for use in industrial processes. For the purpose of developing our prototype reactive nitrogen life cycle impact assessment method, we developed characterization factors for N-containing compounds from two sources. First, we calculated characterization factors for all nitrogen-containing compounds already listed among the International Reference Life Cycle Data System (ILCD) resource, product and waste flows (European Commission 2010). At present, the ILCD contains over 40,000 flows based on 3,051 unique

Table 1 Non-exhaustive list of chemical formulae and N_r equivalent characterization factors for emissions of a subset of common nitrogen-containing compounds. The full suite of chemicals may be accessed as an Excel-based file in the Electronic Supplementary Material

Nitrogen compound	Chemical formula	Characterization factor kg N_r equivalent/kg
Dinitrogen	N_2	0
Nitrogen monoxide	NO	0.467
Nitrogen dioxide	NO_2	0.304
Nitrous acid	HNO_2	0.298
Nitric acid	HNO_3	0.222
Nitrous oxide	N_2O	0.636
Dinitrogen trioxide	N_2O_3	0.368
Dinitrogen tetroxide	N_2O_4	0.304
Dinitrogen pentoxide	N_2O_5	0.259
Amide ions	NH_2^-	0.875
Nitride salts	N^{3-}	1.00
Nitrogen oxides (as NO)	NO_x	0.466
Ammonium nitrate	NH_4NO_3	0.350
Ammonia	NH_3	0.824
Ammonium ion	NH_4^+	0.778
Hydrazine	N_2H_4	0.875
Nitrate	NO_3^-	0.226
Nitrogen tri-iodide	NI_3	0.035
Nitrocellulose	$C_20H_{16}N_4$	0.500
Nitroglycerine	$C_3H_5N_3O_9$	0.185
Trinitrotoluene	$C_7H_5N_3O_6$	0.185
N_r in protein	Various	0.160 (average)
N_r in amino acids	Various	Various
Other organic N	Amines, amides, nitro groups, imines, enamines	Various

Chemical Abstracts Service (CAS)-numbered chemicals (CAS 2012). Of these, 1,462 contain nitrogen. Second, we screened the 2007 Organization for Economic Cooperation and Development (OECD) High Production Volume (HPV) chemical list (OECD 2012) of 4,636 substances for additional CAS-numbered compounds that both (a) contain nitrogen and (b) have an assigned chemical formula in the Sci-Finder (2012) index. The OECD HPV chemical list records chemicals which are produced at levels greater than 1,000 tonnes per year in at least one member country/region. This resulted in the identification and characterization of an additional 630 nitrogen-containing chemical substances. The full suite of chemicals (by CAS number) and draft characterization factors may be accessed as an Excel-based file in the Electronic Supplementary Material for this manuscript.

It should be noted that, in addition to those identified and characterized, the OECD HPV chemical list includes numerous other nitrogen-containing chemicals for which chemical formulae are not available because they do not have precisely fixed chemical compositions. This includes, for example, important, high-production volume petroleum compounds, materials of biological origin such as proteins and amino acids (and materials which contain them), and numerous other organic compounds. In such cases, researchers wishing to implement a nitrogen impact assessment in process-based LCA must identify characterization factors for these compounds in addition to those we present. In some cases, generic factors might be applied—for example, using the average N content of protein (16 %) in combination with protein content data for materials of biological origin.

Also important to consider in order to avoid potential double counting is uptake of previously emitted fixed N by biomass used or produced in a given life cycle—for example, N deposition on croplands and uptake by crops, or uptake of leached nitrate by biomass in aquatic systems. Here, any such fixed N inputs (which are effectively cycling via nitrogen cascades) should be subtracted from the inventory.

2.3 Methods application: quantifying losses of fixed N associated with consumption in the EU-27

In order to evaluate the efficacy of this simplified method and prototype supporting set of characterization factors for consistent inventorying of anthropogenic mobilization, flows and losses of fixed N in life cycle assessment, we implemented the method for a life cycle inventory data set representing a subset of EU-27 consumption at the consumer level for the year 2006. The inventory data set used was that compiled to support development of the European Commission Basket-of-Products Indicator (European Commission 2012a, b).

The Basket-of-Products (BoP) Indicator inventory data represent the resources used and associated emissions for a subset of the final consumption of products for an average citizen in the EU-27 over the entire life cycle of goods and services (production, use, end-of-life) (European Commission 2012b). Specifically, it covers the apparent per capita domestic final consumption of representative products in several key demand categories, i.e. nutrition, shelter (high-rise, multi-family, and single-family dwellings), consumer goods and mobility (Table 2).

3 Results and discussion

3.1 Basket-of-Products Indicator results

For the Basket-of-Products Indicator life cycle inventory (LCI), the calculated life cycle fixed nitrogen emissions

attributable to average consumption of the modelled products in the key demand categories in 2006, including production, use and end-of-life phases, amounted to 8.3 kg per capita. Of these, almost 100 % were in the form of emissions of ammonia (38 %), nitrogen dioxide (33 %), nitrate (24 %), nitrous oxide (4 %) and nitrogen monoxide (1 %). Emissions were also assessed based on life cycle stage (production, use, and end-of life) and demand category (Fig. 1). On this basis, it was determined that the "nutrition" demand category—specifically, the (food) production phase—accounted for 63 % of total emissions (and 90 % of production-related emissions overall). The total attributable to nutrition would actually be higher were nutrition-related emissions at the use and end-of-life phases not attributed to the shelter demand category (i.e. where most food is prepared and consumed, and associated wastes are released). The second largest share of emissions (19 %) is attributable to the shelter demand category, largely for the use phase. This relates both to the consumption of food and associated waste flows, as well as emissions linked to household energy consumption. The use phase of the mobility demand category is also significant (11 %). Production and end-of-life phases make minor contributions (2 % each) across the consumer goods, mobility and shelter demand categories (see Fig. 1).

Within the nutrition demand category, 55 % of emissions were attributable to dairy products and eggs, and 34 % to meat and seafood (Fig. 2). In contrast, crop-based products (for direct human consumption) contributed only 5 % and beverages 7 %.

Table 2 Demand categories and representative products considered in the Basket-of-Products Indicator life cycle inventory data set

Demand category	Product group	Representative products
Nutrition	Meat and seafood	Beef, pork, poultry
	Dairy products and eggs	Milk, butter, cheese
	Crop-based products	Sugar, vegetable oils and fats
	Vegetables	Potatoes
	Fruits	Apples, oranges
	(Non-)alcoholic beverages	Coffee, beer
Shelter/private housing	Single-, two-family and terrace houses	Single house
	Multi-family houses	Multi-family house
	High-rise buildings	High-rise building
Consumer goods	Clothing	Shoes, cotton shirt
	White goods	Washing machine, refrigerator, dish-washer
	Consumer electronics	Laptop
Mobility	Private transport	Mid-class car
	Public transport	Travel by train, bus and plane

However, it should be noted that, of the 1510 nitrogen-containing compounds in the current ILCD flow list, only 37 appear in the life cycle inventory data set used in the Basket-of-Product Indicators prototype. Although potential contributions of these additional chemicals to total emissions are likely small individually, the aggregate contribution may be significant.

3.2 Comparison of results to other studies

The BoP framework matches statistics on private per capita consumption in key demand categories with LCI data for representative products in each category, including resource use and emissions across the life cycle. This represents a subset of flows attributable to total per capita consumption. The aim of the BoP is to provide an index for monitoring and analysis rather than a quantification of absolute environmental impacts per person (European Commission 2012b). It is hence somewhat difficult to draw direct comparisons with consumer-level nitrogen footprints reported elsewhere, which aim for more comprehensive coverage of overall consumption.

Nonetheless, the dominance of the nutrition demand category in contributing to fixed N emissions (63 %) in the BoP inventory is consistent with previously published analyses, although the proportion is lower than the 71 and 90 % reported by Leach et al. (2012) for the USA and the Netherlands, respectively. Differences in average dietary consumption patterns may be influential here.

For the nutrition category, the BoP includes six food groups, i.e. beverages (represented by beer and coffee), crop-based products (represented by sugar and vegetables oils and fats), vegetables (potatoes), fruits (apples and oranges), dairy products (fresh milk, butter and cheese) and meat and seafood (beef, pork and poultry). These groups are similar to those used by Westhoek et al. (2013) and Leip et al. (2013), where total food consumption in the EU-27 was grouped into six vegetable food groups (cereals, potatoes, sugar, oils, leguminous crops and fruits and vegetables) and six animal product groups (beef and veal, pork, sheep and goat meat, poultry meat, dairy products and eggs), in sum representing virtually all food consumption.

Neglecting cereals used for direct human consumption among the representative products (see Table 1) included in the BoP (indirect consumption of cereals via use in production of animal products as well as the production of sugar, fats and oils is, however, included) leads to an underestimation of absolute N emissions related to domestic food production. Elsewhere, using a life cycle-based approach and the CAPRI model, Leip et al. (2013) estimate that 55 % of N emissions are attributable to the cultivation of cereals (including those used for animal feeds). Nevertheless, the ratio of N emissions between vegetable products (13 %) and animal products (87 %) indicated by the BoP inventory is actually quite close to that estimated by Leip et al. (2013)

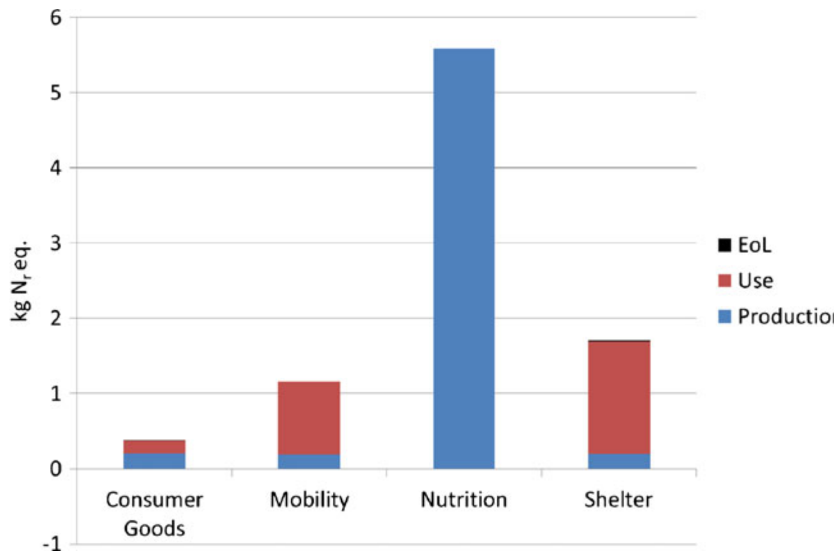

Fig. 1 Emissions of fixed nitrogen associated with consumption of representative products in key demand categories for the average EU-27 consumer in 2006 (by life cycle stage and demand category)

(82 % animal products vs. 18 % vegetable products). Leach et al. (2012) report slightly smaller shares for animal products for the USA (75 %) and the Netherlands (75 %). However, the distribution of emissions between animal products in the BoP differs considerably from results reported elsewhere. BoP results indicate that 62 % of emissions are attributable to dairy products—much more than the 36 % reported by Leip et al. (2013). Differences in allocation strategies across studies may be determining.

In absolute terms, annual energy-related fixed N emissions estimated in the BoP amount to 3.2 kg N per capita, which is well in agreement with the data compiled by Leach et al. (2012) for the Netherlands (2.4 kg N_r per capita). Leach et al. (2012) also compare the results of their analysis to top-down estimates from total NO_x emission inventories. For the USA, the N-footprint calculated with their bottom-up methodology accounts for 63 % of total NO_x emissions over the US territory (import/export flows are not considered). An analogous calculation for the Netherlands based on total NO_x emissions of about 110 Gg N per year (van Aardenne et al. 2009; Leip et al. 2011b) suggests total annual energy-related emissions of more than 6 kg N per capita. It should also be noted that the scope of the energy-related fixed N emissions (housing, shelter, transport) included in the BoP inventory is wider than that of the analysis by Leach et al. (2012) in that it includes all stages of the life cycles of the relevant products, including production, use and end-of-life processes.

Besides the nutrition demand category, only the consumer goods demand category has higher emissions in the production phase (54 %) than in the use phase. However, the total contribution of consumer goods to overall fixed N emissions is only 4 % (or 11 % not considering nutrition). In contrast, the use

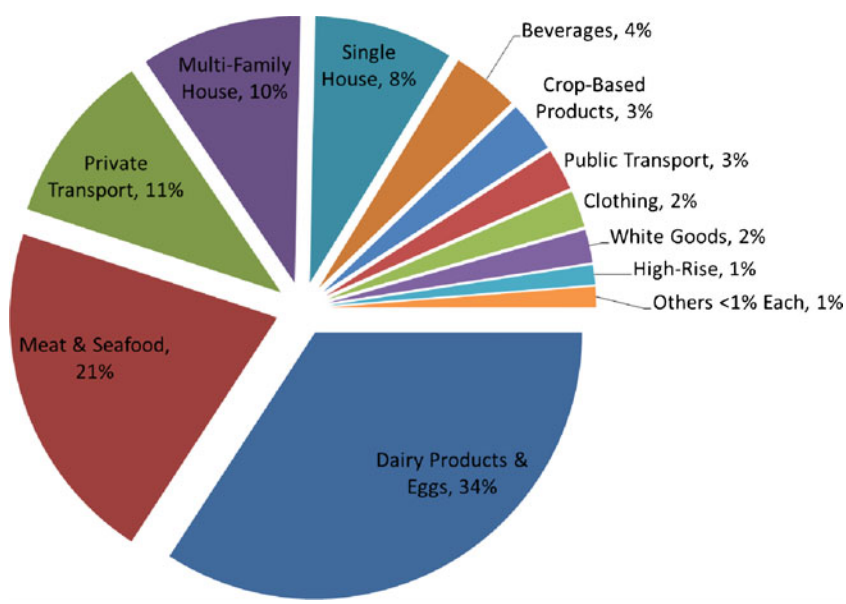

Fig. 2 Emissions of fixed nitrogen per demand category considered attributable to consumption of representative products by the average EU-27 consumer in 2006

phase dominates fixed N emissions over the life cycle (82 %) in the mobility and shelter demand categories. This is consistent with earlier observations that, after food production, combustion of primary energy carriers is the second most important source of fixed N emissions. According to Leip et al. (2011b), 96 % of NO_x emissions are attributable to combustion processes in households, transport and industry. Data from EDGAR-CIRCE (van Aardenne et al. 2009) suggest that 55 % are emitted from transport and residential combustion, while industrial emissions contribute 13 % for a total of 3.4 Tg N per year for the EU-27.

It should be noted that the very small contribution of the end-of-life phase to fixed N emissions across demand categories may reflect that the fate of many N containing compounds (for example, those destined for landfill) is not adequately accommodated in the BoP life cycle inventory, rather than the true extent of emissions. Indeed, this hypothesis is supported by our observation that only a very small subset of N-containing flows for which we developed characterization factors are represented in the BoP inventory. This may be due to the fact that many nitrogen-containing materials, although substantial in volume (i.e. as suggested by their representation on the OECD HPV chemical list), do not contribute to the other impact categories originally considered for the BoP indicator beyond a cut-off criteria threshold and were hence excluded from the final inventory. Indeed, this may be true of many historically compiled life cycle inventories, potentially presenting problems for the initial implementation of anthropogenic perturbation of the N cycle as an impact category in LCA studies.

4 Conclusions and recommendations

The critical role of reactive nitrogen in a spectrum of both environmental and human health concerns at local, regional and global scales, coupled with its central importance in food production and other industrial processes, suggests that reducing human perturbation of the nitrogen cycle may figure among the most challenging dilemmas yet encountered by industrial society (Rockstrom et al. 2009). In light of increasing evidence of anthropogenic perturbation of the global nitrogen cycle via on-going high levels of nitrogen fixation and losses, increasing human demands for and dependence on nitrogen, and the attendant impacts on environmental, health and human welfare outcomes, we argue for stand-alone treatment of nitrogen in life cycle inventories and impact assessments. We do not suggest that similar methods are desirable for every other element or biogeochemical cycle, although in specific cases (for example, the water and phosphorus cycles), this may indeed be merited.

Overall, the results generated by applying our method and characterization factors to the Basket-of-Products life cycle inventory data set are consistent with those observed from studies having a similar scope but different methodological approach. This outcome suggests that N can, indeed, be systematically inventoried and aggregated in process-based LCA for the purpose of providing information for decision support, using the methods and characterization factors we propose. Specifically, the method enables quantification of the extent to which product life cycles (or consumption patterns) contribute to anthropogenic perturbation of the N cycle. However, the inventories produced for such analyses can also support identification of life cycle fixed nitrogen emission hotspots, differentiation of products on the basis of N intensity and/or N-use efficiency, and quantification of N footprints at the level of individual products or consumption profiles. This includes considerations of “embodied” N in traded goods and the impact of trade in terms of N flows, generally. In turn, the information derived may support a variety of applications, including supply chain management, product benchmarking and labelling, or even policies targeting improved nitrogen management. Indeed, treatment of nitrogen within the broader context of multi-criteria life cycle assessments is essential to preventing burden-shifting in the formulation of improved N management strategies.

We underscore, however, that initial implementation of this method may potentially be hindered by the historical lack of attention to major N-containing flows in some existing life cycle inventories. We also highlight that, despite having defined characterization factors for over 2,000 compounds, including all N-containing compounds on the OECD HPV list for which specific chemical formulae are available, researchers wishing to implement this method will still be required to derive characterization factors for N-containing materials which do not have a fixed chemical composition—in particular, products derived from fossil fuels and other organic materials, where chemical composition varies. Nonetheless, in light of the increasing recognition of the environmental relevance of N, we encourage researchers to apply our recommended method and characterization factors in order to quantify and report the magnitude and distribution of reactive nitrogen mobilization, flows and emissions associated with product life cycles in process-based LCA.

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